Communication and Interaction With Semiautonomous Ground Vehicles by Force Control Steering

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Communication and Interaction with Semi-autonomous Ground Vehicles by Force Control Steering

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***Abstract*—While full automation of road vehicles remains a future goal, shared-control and semi-autonomous driving – involving transitions of control between the human and the machine – are more feasible objectives in the near term. These alternative driving modes will benefit from new research towards novel steering control devices, more suitable where the machine intelligence controls only partially the vehicle.**

In this paper it is proposed that when the human shares the control of a vehicle with an autonomous or semi-autonomous system, a force control or non-displacement steering wheel (i.e., a steering wheel which does not rotate but detects the applied torque by the human driver) can be advantageous under certain schemes: tight rein or loose rein modes according to the H-metaphor. We support this proposition with the first experiments, to the best of our knowledge, in which human participants drove in a simulated road scene with a *force control steering wheel*. The experiments exhibited that humans can adapt promptly to *force control steering* and are able to control the vehicle smoothly.

Different transfer functions are tested, which translate the applied torque at the *force control steering wheel* to the steering angle at the wheels of the vehicle; it is shown that fractional order transfer functions increment steering stability and control accuracy when using a force control device. Transition of control experiments are also performed with both, a conventional and a *force control steering wheel*. This prototypical steering system can be realized via *steer-by-wire* controls, which are already incorporated in commercially available vehicles.

***Index Terms*—Human-machine integration, Steering control, Cybernetics, Haptics, Steer-by-wire, Ground vehicle automation**

I. Introduction

A. Background

During recent years, news broadcasting of science and technology trends has placed a special interest in the possibility of driverless cars pervading the public roads. In spite of the eager news coverage, fully autonomous vehicles may not materialize in the short term – or not materialize at all [1]. There are a number of technical challenges which presently do not have a clear solution. Conceivably, the most hindering obstacles are amidst the domain of Artificial Intelligence (AI); the way in which artificial neural networks generalize is not yet fully understood [2], and they can be easily fooled by perturbations in the input data [3].

Although conventional cars will not attain full automation anytime soon, early generations of associated developments will potentially result. An obvious one is the occurrence of autonomous transportation systems within restricted environments. Driverless cars in simplified environments may be implemented. This can be accomplished by adapting the infrastructure. For instance, *eLanes* could be established in which only vehicles in autonomous control mode are allowed to circulate [4]. eLane design would conform to the Operational Design Domain (ODD) of the vehicle. Entering or departing eLanes will entail transitions of control between the human and the machine. Another interesting prospect is that of *shared-control* systems, where the control of the machine is shared between the human and the intelligent system simultaneously [1].

The idea of *shared-control* has been present in the literature for quite some time, yet at present it is gaining momentum. Within the classical literature, the paper by Birmingham and Taylor on human-machine systems [5] is an illustrative case; it is affirmed that, because of the high adaptability that humans exhibit, they should never be removed from the control loop. Instead, the paper suggests, system design needs to be aimed towards *unburdening* the human-operator. Thus it promotes the concept of using transfer functions between the control device and the machine, with the intent of facilitating the operator task. A similar notion is highlighted in a later publication by Licklider, through an alternative strategy. In [6], it was proposed that the human-operator can be temporarily removed from the control loop, but needs to be ready to '...handle the very-low-probability situations...', for which the autonomous system was not designed for. Another *shared-control* approach is the use of *haptic-guidance* [7], [8], in which human performance in enhanced through force feedback.

Since these ideas have been present in the literature for decades, why is the research related to these concepts relevant nowadays? Several recent technological advances help to answer this question. One of them is the so-called *by-wire* controls, which substitute the mechanical connection from a control device to the vehicle actuators with an electronic subsystem. Control *by-wire* has existed in the aerospace industry since the 1980s, but it is only recently that it was incorporated into the automotive industry; in 2014 the first commercially

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available car with *steer-by-wire* (SBW) control was released – the Nissan Infinity Q50. Thus, designing transfer functions between the human and the vehicle – to *unburden* the human-operator – has attained general practicability. SBW systems allow for the integral replacement of conventional steering systems with new synthetic mappings.

A relevant question, tackled in this paper, is the role of the steering wheel in semi-autonomous vehicles. The lateral dynamics of cars have been commonly handled with a steering wheel since their inception. Considering that the control of ground vehicles may be shared between the human and the machine in the future, a conventional steering wheel may not be the best interface device. An elucidating analogy is that of horse-drawn vehicles such as horsecars or stagecoaches, which essentially are shared-control systems where the control is shared between the human and the horse [9], [10]; although the human is in charge of the decisions at the tactical and strategic levels [11], the horse has a certain autonomy at the operational level.

In this paper, the novel concept of a non-displacement steering wheel, or *Force Control Steering Wheel* (FCSW), was examined, as a substitute for the traditional steering system for autonomous and semi-autonomous vehicles. A FCSW is a steering wheel which does not rotate, but detects the applied torque by the human driver. Although new for highway driving, the concept of force control has been applied in the past in a variety of different contexts.

B. Related work

The force control devices that have been tested and/or employed until now, are control sticks (or joysticks) and pointing sticks (or trackpoints). One of the earliest appearances of a force control stick in the literature is found in [12], where force control was applied through a lever in a tracking task and compared with that of a moving lever. The plants controlled by the lever represented proportional, rate and acceleration control; interestingly, force control was shown to be more efficient. In the same publication it is also reported that the participants learned to manipulate the force control device more rapidly. With a similar experimental apparatus, and some years later, McRuer communicated comparable results [13]. For the experiments reported in both publications, the test participants were skilled at tracking tasks – naval officers and pilots.

In [14] a rate force control joystick – thumb controlled – was compared with a computer mouse and with the arrow keys of a computer keyboard. In this case it was concluded that the quickest performance and the lowest error are produced with the computer mouse. Nevertheless, in this case the task at hand did not consist in a tracking exercise; it was a pointing task in which test participants had to select text in a display by displacing a cursor.

In a later paper [15], the comparison between a force control device and a computer mouse – also for pointing tasks – was further studied; it was shown that for pointing tasks a computer mouse is more efficient than a pointing stick, but for the case when pointing is combined with typing, the pointing stick is slightly superior. In the same paper, transfer functions between the forces applied to the device and the pointer speed of linear, parabolic and sigmoid shapes were tested. It was concluded that the sigmoid transfer function yielded the best results. In this case, the force controller was a pointing stick very similar to what today is still incorporated into the ThinkPad laptops, for that research is related to the development of those particular devices by IBM.

ThinkPad trackpoints are perhaps the most well known application of a force control device to date. They are handled through a small hard rubber pad, thus they constitute minimum-displacement sticks. These trackpoints also incorporate a lead-lag compensator producing a *negative inertia* effect to increase pointing performance [16][1], but such an approach is not suitable for when overshooting can produce a fatal accident.

Besides IBM's pointing sticks, there have been other examples of technology products containing some sort of force controller, like the side-sticks in the F-16 fighter aircraft [18], and the C-Stick included in some Nintendo video-game systems, which is used to pan the camera and adjust the field of view. Also, a FCSW was previously utilized in [19] to assess the effects of steering feel, but not as a steering control device for vehicle driving.

In all the discussed cases, the design of the mapping between the applied gain at the force control device and the resultant output was essential. This mapping is highly dependent on the particular control device used, and on the characteristics of the control task.

C. Contribution

In this paper, various hypothesis are studied with respect to driving a ground vehicle with a FCSW. First, it is assessed whether humans are able to drive a simulated vehicle in a typical road scenario *by torque* or *force control steering* (FCS). Tests were conducted at different speeds. Several transfer functions, mapping the applied torque to the steering angle at the wheels of the vehicle, were investigated: constant gain, proportional-integral (PI) filters and fractional order filters.

Another concerning condition, in autonomous driving systems research, is that of control transitions. Driver's reaction time to a potential hazard is typically larger when control transitions are involved [20]. Thus, one of the questions investigated in this paper is the possibility of reducing the reaction time of the driver, when the human regains control from an autonomous system, with a FCSW. To the best of our knowledge, this is the first study in which such FCS experiments are reported. In summary, the contributions of this work are:

- Experiments are conducted to showcase the capability of humans in learning and performing FCS.
- Suitable transfer functions are identified, to transduce the applied torque by the human driver into steering wheel angle. These are based on fractional order filters.
- Additional experiments are conducted to assess the efficacy of FCS when the human has to regain control from an autonomous system.

[1]The concept of negative inertia had been already explored much before by Tustin [17].

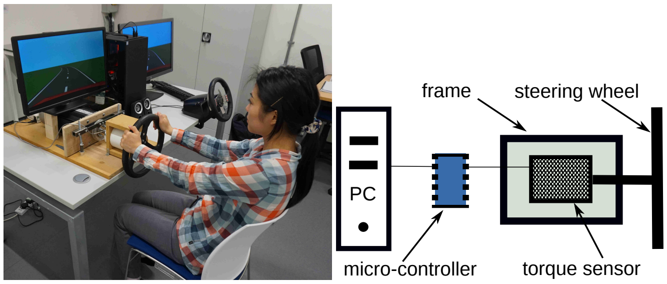

Fig. 1: (a) Experimental setup as presented to the participants. In front of the left display, the FCSW is mounted on a frame. On the right display the Logitech G27 is mounted. (b) Schematic of the FCSW; the steering wheel was locked and attached to a torque sensor in a frame. A micro-controller transferred the sensor readings to a desktop PC. Both control devices interact with the same simulation software on a desktop PC.

- Design guidelines are provided to employ FCS in various shared-control schemes.

The paper is organized as follows. In Sec. II the methodology, experimental setup, participants and experiments are described. These experiments include an adaptation phase and a driving phase. The results from the experiments are examined in Sec. III. In Sec. IV the experiments are discussed conceptually, and a summary of some of the potential applications of FCS, not explicitly studied experimentally in the paper, are provided. Final conclusions are drawn in Sec. V.

II. Methods

Naturalistic driving data are inherently noisy and difficult to analyze [21]. On the other hand, data collected from participants in laboratory tasks, although may be less representative of realistic driving, are more interpretable. For this research, an experimental setup consisting of a simple driving simulator – presenting the forward view scene of a roadway from a ground vehicle – and a FCSW were implemented. Additionally, a Logitech G27 steering wheel was utilized with the same software, as a baseline for comparing performance (Fig. 1). The leading objective of the experiments was to assess and to compare human-performance between both control devices under various conditions: simple tracking tasks, ground vehicle driving at different speeds and regain of control from an autonomous system. For the case of FCS, several transfer functions – translating applied torque to steering wheel angle – are investigated, including fractional order transfer functions.

A. Experimental setup

1) Roadway-vehicle simulation: A computer simulation was designed for the purpose of performing the experiments. The computer graphics were generated in 3D with the Open Graphics Library (OpenGL) API [22]. The display was refreshed at a variable frame rate (of at least 40 Hz); this minimum rate suffices to ensure ideal control performance [23]. The graphical simulation consisted of a forward road scene (Fig. 4a) with varying road geometry for the different experiments. The simulation run in real time at 1000 Hz. At each time step the states of the vehicle simulation were updated through a Runge-Kutta method of order $\mathcal{O}(h^4)$ [24]. The vehicle states were the body slip angle $\beta(t)$ and the yaw rate $\eta(t)$, and were simulated with the linear *single-track* vehicle model found in [25] – Eqs. (1), (2) with the parameters in Tab. I:

$$\begin{bmatrix} \dot{\beta} \\ \dot{\eta} \end{bmatrix} = - \begin{bmatrix} L_0/MU & 1 + L_1/MU^2 \\ L_1/I & L_2/IU \end{bmatrix} \begin{bmatrix} \beta \\ \eta \end{bmatrix} + \\ + \begin{bmatrix} C_{\alpha f}/MU \\ l_f C_{\alpha f}/I \end{bmatrix} \delta \quad (1)$$

with

$$\begin{cases} L_0 = C_{\alpha f} + C_{\alpha r} \\ L_1 = l_f C_{\alpha f} + l_r C_{\alpha r} \\ L_2 = l_f^2 C_{\alpha f} + l_r^2 C_{\alpha r} \end{cases} \quad (2)$$

where $C_{\alpha f}$ and $C_{\alpha r}$ are the *axle cornering stiffness* for the front and rear axle respectively, M is the mass of the vehicle, U the speed – which was a constant value for each experiment, l_f and l_r are the distances from the centre of gravity (CG) of the vehicle to the front and rear axle respectively, I the yaw moment of inertia and δ the steering angle at the front wheels.

Mass of the vehicle M	1500 kg
Distance from vehicle CG to front axle l_f	1.1 m
Distance from vehicle CG to rear axle l_r	1.6 m
Front cornering stiffness (both wheels) $C_{\alpha f}$	55000 N/rad
Rear cornering stiffness (both wheels) $C_{\alpha r}$	60000 N/rad
Yaw moment of inertia I	2500 kg·m^2
Steering ratio r_s	16:1

TABLE I: Vehicle model parameters as set for the driving simulator experiments.

The recorded variables were the simulation time, vehicle position, vehicle heading, yaw rate, lateral offset, body slip angle, steering angle (or torque, depending on the employed control device – Sec. II-A2). While ground vehicles typically display non-linear dynamics, these do not largely differ from the linear regime. For the analysis of steering control linear vehicle models are sufficient.

2) Hardware: Two displays and two control devices – one display for each control device – were connected to the computer that run the simulation (Fig. 1). Speakers were used to signal the driver of varying conditions during the experiments. The two control devices were a Logitech G27 steering wheel, and a FCSW. The motor of the Logitech G27 was controlled from the simulation application to produce a self-aligning torque effect, which was proportional to the lateral force on the front tires [25]. The FCSW was built for this particular experiment and consisted of a torque sensor (Tab. II) attached to a support frame (Fig. 1b). The signal from the torque sensor was read and conditioned by a single-board micro-controller. The simulation application requested the state of the sensor to the micro-controller at each simulation step. When requested, the micro-controller broadcasted the torque sensor back to the application. The communication between the devices was set at $921600\,\mathrm{baud}$ to achieve negligible latency.

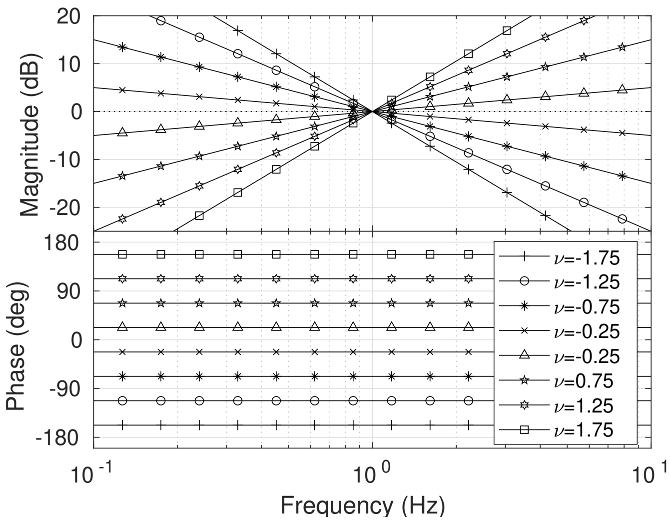

Fig. 2: Frequency response of $1/s^{\nu}$ by varying ν. The slope of the magnitude response is $\nu{\cdot}20\,{}^{\mathrm{dB}}/_{\mathrm{decade}}$ while the phase response is $\nu{\cdot}\pi/2$ rad for $\nu \in \mathbb{R}$.

The steering wheel was configured to rotate 900 deg lock to lock, corresponding to $|\delta| \leq 28.13\,\mathrm{deg}$ with the chosen steering ratio (Tab. I). When driving by torque with the FCSW, these maximum values for δ were achieved with applied torque of $\pm 15\,\mathrm{N}\cdot\mathrm{m}$ ($\pm 4.78\,\mathrm{kg}$) – which was the magnitude limit when reading from the torque sensor (Tab. II).

B. Fractional order filters

Different types of transfer functions – mapping the input to the control device by the human-operator to the vehicle model – were considered. Among the candidates were fractional order transfer functions[2]. In the fractional calculus approach, the traditional notions of integral and derivative are extended to define non-integer powers of the integral and differential operators [26].

For the case of fractional order integration of order $\nu > 0$ of a function f – denoted as $D^{-\nu} f(t)$ – the Laplace transform is given by the relation:

$$\mathcal{L}\{D^{-\nu} f(t)\} = \frac{F(s)}{s^{\nu}}, \tag{3}$$

where $\mathcal{L}\{f(t)\} = F(s)$. The frequency response of $1/s^{\nu}$ with $\nu \in \mathbb{R}$ is shown in Fig. 2. Thus for $\nu = 1$, (3) corresponds to classical first order integration: $D^{-1} f(t) = \int_0^t f(t)$. Fractional order transfer functions have been favourably used for modelling biological systems [27]. In [28], they were employed for modelling human-operators controlling vehicles in a cybernetical control loop [29]. Herein, the advantage of this method relies in that it allows for the introduction of integration in gradual non-integer increments – hence it is convenient for laboratory tasks. Fractional operators provide a simple tuning procedure for adjusting the level of *haptic feel*, as they are described by only one parameter, which can be interpreted as the amount of memory introduced in the system. In [30], the technical background for this approach is discussed in detail.

[2]For this research, the Riemann-Liouville fractional integral was employed [26].

Torque Sensor Model	Omega TQ301-45N
Sensor range	$0 - 45\,\mathrm{N}\cdot\mathrm{m}$
Sensor reading range – limited	$0 - 15\,\mathrm{N}\cdot\mathrm{m}$
Accuracy	$\pm 0.2\,\%$FSO
Steering wheel diameter	0.32 m

TABLE II: Specifications of the torque sensor and the FCSW.

C. Participants

Ten participants of varying age, gender and level of driving experience completed the experiments (Tab. III). All the participants joined voluntarily and, prior to the experiments, signed a consent form[3].

The experiments were executed over two different days, to monitor human adaptation to FCS. Each day comprised approximately 30 minutes of driving with some periods of rest. In all the driving experiments, the visual projection represented a driver view from the left seat of the car – with an offset of 0.45 m. The experiments in Day 1 included a simple tracking task, so that the participants could adapt to the FCSW.

D. Training experiments phase – Day 1

1) Tracking experiment #1: In a first tracking experiment, a red target circle was presented in the display, which varied position along an arc between two alternate locations – corresponding to a torque of $\pm 10.5\,\mathrm{N}\cdot\mathrm{m}$ (Fig. 3). The target changed its position every 20 s, and the total duration of the experiment was 180 s. A blue colored dot represented the applied torque to the FCSW in the display. The participants were requested to apply force on the FCSW in order to place the cursor (blue dot) in the centre of target (red circle).

[3]These tests were approved by the College of Science Research Ethics Committee of the University of Lincoln (U.K.) with UID COSREC491.

PAT.	Age	Gender	D. Lic.	D. Exp	V. Exp
P1	32	M	✓	✓	×
P2	33	M	✓	✓	✓
P3	34	F	×	×	×
P4	41	M	✓	✓	×
P5	25	F	✓	✓	×
P6	28	M	✓	✓	×
P7	22	M	✓	✓	✓
P8	20	M	✓	✓	✓
P9	30	M	✓	✓	×
P10	28	F	✓	✓	×

TABLE III: Gender and age of the 10 participants in the experiments. In the table it is also detailed whether the participants hold a driving license or not, their driving experience (i.e., they drive at least once in a week) and if they play video-games frequently (i.e., at least once in a month).

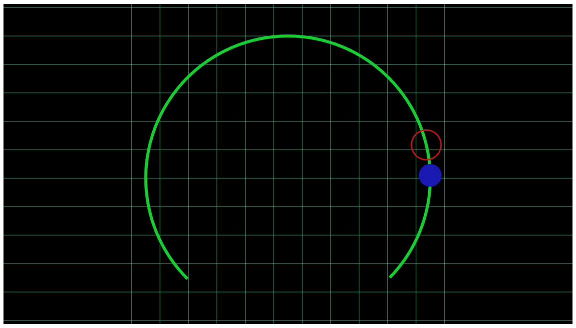

Fig. 3: Visual display as in the tracking experiments #1 and #2 during Day 1. The participants had to apply torque to the FCSW to position the cursor (blue dot) inside the target (red circle) – which varied its position at each time interval. The cursor and target moved only over the circular arc (green dial), with rest state at its topmost position.

2) Tracking experiment #2: The second FCS tracking experiment was very similar to the first and had the same duration (180 s). The only differences were that the target changed position more frequently – every 6 s – and at randomized locations over the dial.

During the training phase (Day 1) other experiments were included which involved driving with the Logitech G27 and with the FCSW in tracks of different geometry. These experiments were also performed for adaptation purposes, thus are not explicitly described here. Nevertheless, some of these experiments are compared with those of Day 2 in Sec. III.

E. Performance measurement experiments – Day 2

The experiments in Day 2 comprised driving at different speeds with the FCSW and a regain of control experiment, which was carried out with both control devices (steering wheel and FCSW).

The participants drove with the FCSW in a simulated road scene (Sec. II-A1) through a pseudo-randomly generated road at $30, 50$ and $70\,{}^{km}\!/\!_{h}$. Each experiment was performed at a constant speed. While this is not a fully realistic driving scenario, the recorded signals can be considered stationary and comparisons among subjects are feasible. The road geometry was produced by a Perlin noise generator [31] (Fig. 4a). The emphasis of these experiments was placed on investigating potential transfer functions between the torque sensor and the vehicle model. These are summarized in Tab. IV and discussed in more detail in the following.

As a baseline, a transfer function consisting only of a constant gain was first considered. The value of this gain, and the values of the parameters of the other transfer functions, were tuned empirically before the experiments by informal testing by the researchers. This was done so that the number of experimental variants presented to the participants were kept at an acceptable level; the parameters where identical for all the participants (Tab. IV).

A fractional order integrator was also considered as candidate transfer function – Eq. (3). As the experiments involved driving within the simulation at distinct speeds, the index of fractional

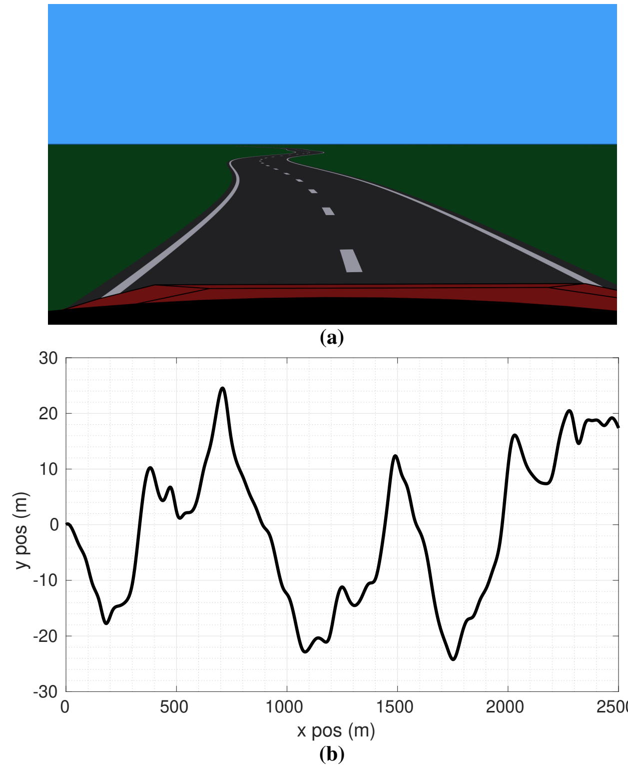

Fig. 4: (a) Forward view of the simulated road in the driving experiments. (b) Sample of the road geometry for a pseudo-randomly generated road – Perlin noise.

	Gain	**Fractional**	**PI**
speed	K_p	$\frac{1}{s^{\nu}}$	$K + (1-K)\frac{1}{s}$
$30\,{}^{km}\!/\!_{h}$	0.75	$\nu = 0.05$	$K = 0.5$
$50\,{}^{km}\!/\!_{h}$		$\nu = 0.25$	$K = 0.6$
$70\,{}^{km}\!/\!_{h}$		$\nu = 0.35$	$K = 0.7$

TABLE IV: Transfer functions of the filters employed during the FCS experiments that translate torque to steering wheel angle.

integration was tuned empirically for each speed value (Tab. IV). In prior informal tests it was observed that higher order of fractional integration was better for higher speeds. In addition, to contrast the effects of the memory added by the fractional operator with a standard approach, a PI filter was also examined. The PI filter was constrained to a single parameter, to match the interpretation with the fractional filter. As the PI filter involves a pure integral with a very extreme memory effect – as compared to low level fractional integration – it was observed that lowering the effect of the integrator was seemingly better at higher speeds (Tab. IV).

1) FCS at $30\,{}^{km}\!/\!_{h}$: This experiment consisted of driving during 5 min with a FCSW on a simulated roadway – which was the same for all the participants (Fig. 4). To avoid the introduction of bias by the particular road geometry, half of the participants drove the road in the opposite direction as compared to the other half. The simulation represented a vehicle

Phase #	Transfer Function	Duration
1	Gain: K_p	60 s
2	Fractional: $1/s^{\nu}$	60 s
3	PI: $K + (1 - K)\frac{1}{s}$	60 s
4	Fractional: $1/s^{\nu}$	60 s
5	PI: $K + (1 - K)\frac{1}{s}$	60 s

TABLE V: Filter used at each of the phases of the driving experiments with the FCSW. Their specifics are defined in Tab. IV

with a constant speed of $30\,{}^{km}/_{h}$ and the driver sitting at the left seat of the car. Every 60 s, an acoustic signal and an intermittent change in colour in the background sky indicated to the driver that a change in the dynamics of the vehicle had occurred; the test participants had been informed about this procedure before the experiment was conducted. Also, the participants had performed a similar experiment in Day 1. The change in the dynamics reflected a different transfer function between the torque sensor and the vehicle model. The order in which the transfer functions were presented is specified in Tab. V. Thus the experiment consisted of five phases.

2) FCS at $50\,{}^{km}/_{h}$: This experiment is analogous to the one above (Sec II-E1), with the exception of the vehicle speed, which in this case was $50\,{}^{km}/_{h}$. An identical experiment to this one had been performed in Day 1, as part of the adaptation process to the FCSW. During the first day of the experiments, the participants drove the simulation with the steering wheel, on the same road and at the same speed.

3) FCS at $70\,{}^{km}/_{h}$: The same experiment as above (Sec II-E1) was also performed at $70\,{}^{km}/_{h}$.

4) Regain of control experiments: These experiments were designed to test if the reaction time of the human driver, when regaining control from an autonomous system, can be reduced with a FCSW. For this, two essentially identical experiments were executed by every participant, in which the only difference was the employed control device (steering wheel or FCSW).

In the regain of control experiments, the participants were asked to look at the OpenGL simulation while the vehicle drove autonomously through a curved road geometry[4] (Fig. 5), while keeping the hands off the steering wheel (or FCSW). The display was temporarily occluded two times during the simulation, to mimic the effects of switching attention to secondary tasks, such as checking a cell phone. After the second full display occlusion was cleared, and the participants could see the road again, an acoustic signal – and an intermittent change in background colour – notified the drivers to hold the steering wheel (or FCSW) and regain control of the vehicle[5], to avoid a collision with a near obstacle, a cuboid of width half of that of the road and two meters tall.

Although the experiments with the steering wheel and the FCSW were identical, in order to minimize bias effects, the participants were told that both experiments were different. Half of the participants performed the experiment first with the FCSW, while for the other half the order was reversed (steering wheel first). Both experiments were executed at $50\,{}^{km}/_{h}$. For the case of the FCSW, steering control was implemented with the fractional transfer function (Tab. IV). In Fig. 5, the various phases of the experiment are shown over the road geometry.

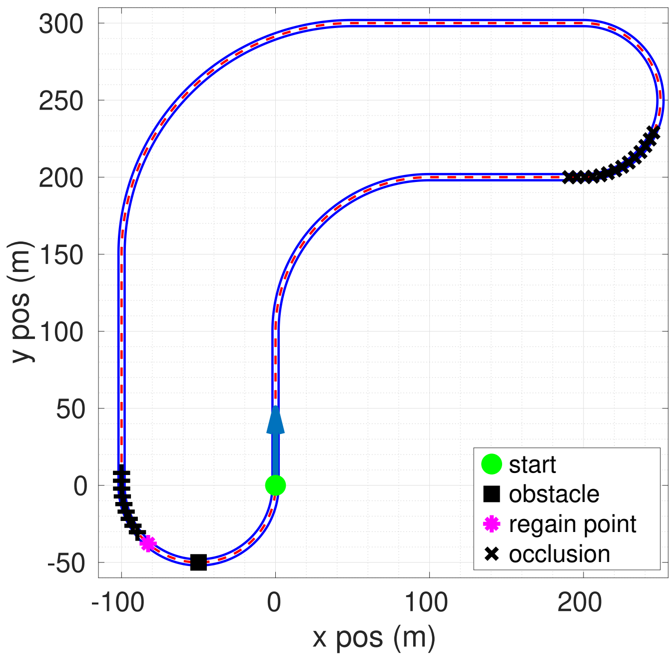

Fig. 5: Road geometry in the regain of control experiments, displaying the occluded regions, the obstacle position and the regain of control point.

III. Results

A. Training experiments phase – Day 1

1) Tracking experiment #1: The participants adapted promptly to the test, with the exception of two of them. Participants P3 and P4 found that it was difficult to maintain the degree of torque ($\pm 10.5\,\mathrm{N \cdot m}$) for 20 s. Nevertheless, once they improved their hand positioning strategy, they also became adapted to the FCSW.

2) Tracking experiment #2: All the test participants were able to track the target during this exercise. Besides accustoming the participants to FCS, one of the motivating factors for these two initial tests was to determine if humans exhibit arm tremors when holding the FCSW – due to isometric muscle contraction – at particular frequencies. Peaks in the power spectrum at specific frequencies during isometric contraction are reported in the literature, and this has been suggested as evidence of coordinated and rhythmic neural firing [33]. In our data, characteristic peaks at specific frequencies were not found. It is possible that, because the participants used both hands to control the FCSW, hand tremors were filtered out by both hands acting in anti-phase and muscle co-contraction. Another possibility is that the rubber element that held the steering wheel fixed partially filtered out the tremors.

[4]This was done through an implementation of the Salvucci and Gray model [32].

[5]The participants had already performed a very similar, but much easier test prior to this one, so they were familiar with all the elements found in the experiment: autonomous driving, temporary occlusion, and regain of control to avoid an object in the centre of the road.

B. Performance measurement experiments – Day 2

1) FCS at $30\,{}^{km}\!/\!_{h}$*:* Fig. 6a shows the mean squared error (MSE) of the lateral offset from the centre of the road for each participant and at each phase of the experiment. The figure also includes box plots averaging the results. Because the MSE was fairly similar during the experiment for each transfer function setting (Tab. V), only the aggregated value for each experimental variant is reported. The responses of P4 were in the outlier range for these experiments, hence not included in the analysis; P4 drove routinely with a large offset from the centre of the road with both control devices.

At $30\,{}^{km}\!/\!_{h}$, the participants produced larger MSE with the PI transfer function as compared with the baseline transfer function – proportional gain – and the fractional order integrator. And although the second time the PI transfer function appeared the participants improved their performance, they adapted faster to the fractional order filter. An ANOVA test was performed (95% confidence) to compare the mean performance (MSE) among three groups, corresponding to the three tested transfer functions. The null hypothesis was that the data does not show significant differences among the group means. Although we observed differences among the conditions, these were not significant at $30\,{}^{km}\!/\!_{h}$: $[F(2,42) = 0.45,\ p = 0.64]$. This is likely caused by the relatively small sample size, resulting in a low power test.

2) FCS at $50\,{}^{km}\!/\!_{h}$*:* Fig. 6b displays the evolution of the MSE through the different phases of the experiment. The solid dots are the median of the MSE among all the participants in Day 1. The box plots summarize the results for the same experiment in Day 2; there was a consistent improvement in performance on the second day. The blue line indicates the median performance with a steering wheel. It is noticeable that the participants showed a lower MSE with the FCSW, but this may be related to the characteristics of the employed Logitech steering wheel and the vehicle simulation, which may not necessarily mimic fully realistic driving. However, this was unanticipated, and several participants were surprised by how easy their FCS task was during Day 2.

In Fig. 7, the steering movements produced by P7 in this experiment with the FCSW and with the steering wheel (Day 1) are compared. For the FCSW, the signal is shown before and after the fractional order filter was applied. The steering signal in the FCSW is composed of shorter pulses but of higher amplitude than those of the steering wheel. The hypothesis that human operators employ ballistic intermittent corrections while in a control task is a subject of active research [34]. This effect is more clearly manifested when using joysticks or force control devices than when maneuvering with a steering wheel [21].

At $50\,{}^{km}\!/\!_{h}$ the differences between the tested transfer functions (Tab. IV) were larger than those at $30\,{}^{km}\!/\!_{h}$; the fractional transfer function yielded the lowest median for the MSE. The PI filter was the worst performer together with the proportional transfer function. Adaptation to the PI filter was also worse than at $30\,{}^{km}\!/\!_{h}$, although the variance among participants is reduced (Fig. 6b). At $50\,{}^{km}\!/\!_{h}$ the ANOVA test yielded a smaller p-value than at $30\,{}^{km}\!/\!_{h}$, although not yet

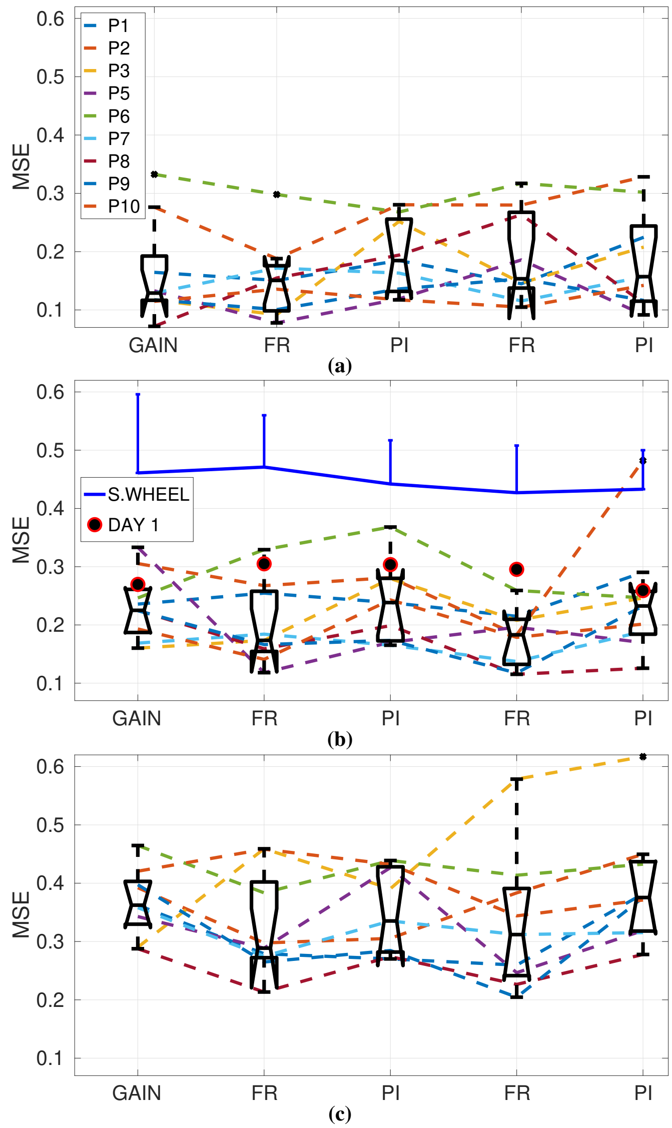

Fig. 6: MSE for each participant and for each phase of the FCS experiments at (a) $30\,{}^{km}\!/\!_{h}$, (b) $50\,{}^{km}\!/\!_{h}$ and (c) $70\,{}^{km}\!/\!_{h}$. Box plots aggregating the data are also included in each figure. In the box plots, the box edges mark the $25th$ and $75th$ percentiles, while the notches indicate 95% confidence intervals for the median. The box *whiskers* extend to a maximum of 1.5 the interquartile difference. In figure (b), the median values of the lane keeping error (MSE) in Day 1 and for the same experiment are also shown (solid dots), along with the performance with the Logitech steering wheel (blue line) over the corresponding track segments. The vertical blue lines indicate the variance of the squared errors.

significant $[F(2,42) = 2.55,\ p = 0.09]$.

3) FCS at $70\,{}^{km}\!/\!_{h}$*:* At this speed, the differences between transfer functions were even more pronounced, but the results were very similar; the proportional and the PI transfer functions were the worse performers (Fig. 6c). The lowest MSE was again obtained with the fractional order filter. In this case, the ANOVA test (95% confidence) clearly rejected the null

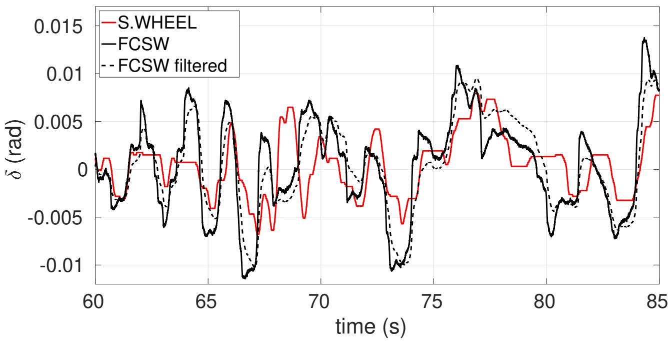

Fig. 7: Comparison of the steering signals from the FCS experiment at $50\,{}^{km}/_{h}$ (Day 2), and the driving test with the steering wheel through the same pseudo-randomly generated road for P7 and with the fractional order filter (Day 1).

hypothesis: $[F(2, 42) = 5.16, p = 0.011]$. Thus the data suggests statistically significant differences among the tested transfer functions at higher speeds.

4) Regain of control experiments: In Fig. 8a, the path of the vehicle's centre of gravity (CG) for all the participants and with each control device is displayed – from the time they were requested to regain control by the system. The participants yielded higher distance margins from the obstacle and faster return to the driving lane with the FCSW. All the participants decided to steer tangentially to the road, with the exception of P9 when using the FCSW.

Fig. 8b shows the steering movements of P6 with both control devices, and during the obstacle avoidance manoeuvre; generally all the participants produced a higher amplitude response in a shorter time with the FCSW. This is most likely caused by the fact the FCSW does not involve arm displacement, nor visual assessment about the current rotation angle of the steering wheel. Further, a t-test (99% confidence, paired and one-sided) was performed over the difference in minimum distance to the obstacle among conditions (steering wheel or FCS) – $M = 1.81$, $SD = 1.21$. The test shows a statistically significant difference between conditions: $[t(9) = 4.74, p = 0.00053]$; the recorded data is in agreement with FCS being advantageous under the tested simulated scenario.

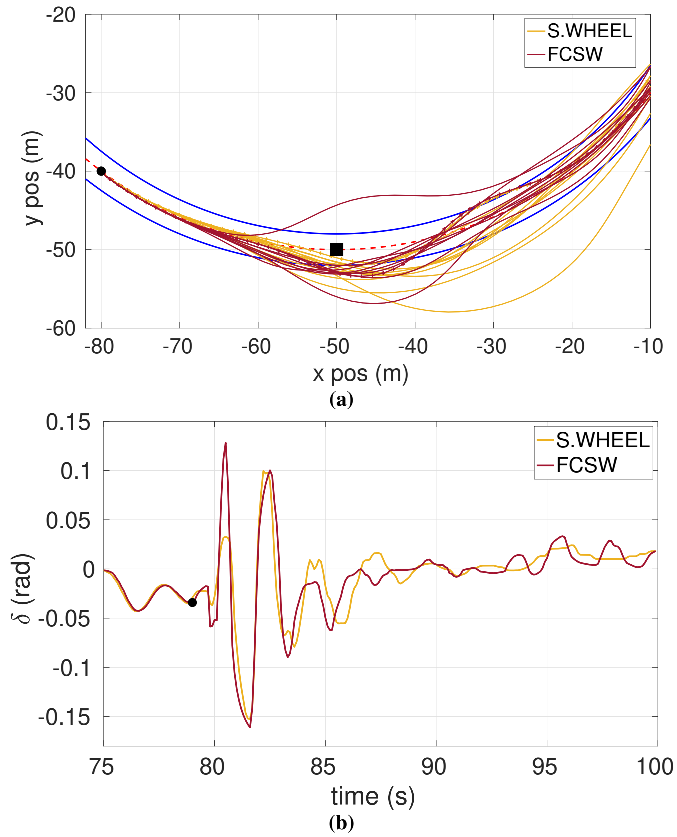

Fig. 8: (a) Path of the CG of the vehicle for all the participants in the regain of control experiments (Sec. II-E4). The blue lines display the position of the left and right boundary lines, while the red dashed line represents the middle lane line. (b) Steering signal in the regain experiments for P6. The black dot marks the point at which the control was transferred back to the driver.

IV. Discussion

A. FCS experiments analysis

Given the observed difference in performance between the fractional and the proportional transfer functions (Fig. 6), it is suggested that filtering becomes more necessary as the vehicle speed increases. Even so, the extreme memory effect of a classical integral – in the PI transfer function – makes the vehicle more difficult to stabilize at higher speeds, as it is shown in Fig. 6c and in the ANOVA test (Sec. III-B3). Indeed, several participants claimed that the PI controller felt *notably lagged*. Thus fractional order filters are reasonable candidates, but other transfer functions not examined here could offer similar performance, such as second order or higher order filters and weighted averages. Nevertheless, fractional order filters present the advantage that they model memory effects explicitly, while they still allow for their analysis from a dynamical systems perspective. Further, as a fractional integrator involves only one parameter – aside from the gain constant – it is easily tuned. Another justification is the evidence that the neuromuscular system presents fractionality [27], [30]. As a FCSW involves static control, the viscoelastic response of the muscles may be altered, and a fractional filter could act as a compensator. This is compatible with the fact that at higher speeds larger fractional integration is needed; humans will hold more tightly a steering wheel when driving under higher workload, increasing their arms mechanical impedance to achieve greater limb stabilization.

With respect to what causes force control to improve performance – for the here reported cases and previous literature (Sec. I-B) – different explanations can be recognized. Response delays are smaller with a joystick than with a steering wheel [30]. A joystick involves a lower ratio between hand movement and control gain than a steering wheel. In the same manner, a force control device reduces the motion required to generate a control pulse to its lowest point. On the other hand, control with a joystick is less precise [35], due to uncomfortable arm positioning – as compared to the steering wheel – and muscle and tendon vibration. The steering signal in the FCSW incorporates some of the features of joystick control; it is composed of shorter pulses but of higher amplitude than those of the steering wheel (Fig. 8b). Thus the FCSW somewhat combines the comfort of the steering wheel with the rapid control actions of a joystick. This is manifested by the notable results in the regain of control experiment (Sec. II-E4); the participants avoided the obstacle with larger safety margins and they were able to stabilize the vehicle in a shorter time.

One advantage of FCS is the possibility that the hands may use the control device to stabilize the arms, thus reducing even more hand vibrations and instabilities – at least for the case of laboratory tasks or when controlling vehicles remotely; in [36], it was shown that the viscoelastic properties of muscles are adjusted to produce smooth and stable hand movements through *viscoelastic regulation*. The same idea was claimed by Kawato in [37]. And in [38], it was studied how the CNS increases impedance in unstable directions of arm motion, also with the intent of generating smoother control movements. Thus a part of any control strategy involves stabilizing the arm itself. With a force controller, arm stabilization is achieved by just holding the device, and all the effort can be directed towards the control action itself. The reduction of arm vibration has another advantage; it is known that externally induced tendon vibration can alter human's perception on applied force [39], thus a fixed arm position could improve control precision.

Another important advantage is that an operator, controlling a force control device, does not need to look at the hand to assess visually the control input produced by an autonomous system, thus unloading the visual channel of control device supervision. It is known that when the hand is not visible visual drift occurs [40]. Hence, in low visibility conditions, force control devices may reduce ambiguity in the control responses when regaining control from an autonomous system or interacting with a shared-control system.

B. Critique

This work does not intend to propose ground vehicles being driven with a FCSW. For example, in semi-static manoeuvres such as parking a vehicle, it can be difficult to assess the wheels turning angle based only on steering feel. Indeed, the relation between torque and steering feel is known to be non-linear [19]. Thus semi-static manoeuvres have not been tested. Additional challenges are vehicle vibration and the lack of direct feedback on the autonomous system input when in shared-control mode. Nevertheless the presented study suggests several implications about force control for highway driving, when using a FCSW as a communication device between the human and a intelligent system assisting in the driving task.

C. FCS design guidelines

There are a number of schemes, not tested here, in which the FCSW could attain real applicability outside of laboratory tasks. Perhaps the most relevant application is the design of shared-control systems. It has been long recognized that, although vehicle technologies must be aimed at *unburdening* the human-operator, full automation is impractical in many situations [5]. Thus, as humans are better controllers of plants with uncomplicated dynamics, SBW technology could be employed to reduce driving to a more simple task, in which steering control is shared between the human and an intelligent system.

One of the difficulties in designing shared-control systems, is in determining the degree of control that the intelligent system shares with the human. In [41] this concept is referred to as the *Level of Haptic Authority* (LoHA), and it specifies the resisting force of the control device to the applied force by the human. Thus the LoHA is set to establish how much of the control task is taken from the human-operator by the intelligent system. An analogous and very illustrative concept is that of the H-mode [10], which compares shared-control to holding the reins of a horse more tightly – manual control from the human-operator – or more loosely – highly automated system. This is usually known as the H-metaphor.

Normally, the control task at hand and the H-mode cannot be considered independent of each other; the impedance of the steering wheel may change the control response of the human, in the same manner as muscle impedance changes the stability of motor control. A FCSW *orthogonalizes* the control signal from the H-mode; thus it is a control device specially well suited to act as a baseline in the implementation of shared-control systems.

An interesting question is what is the role of a steering wheel rotating in a vehicle when in autonomous driving mode. Thus a steering wheel could lock itself as a FCSW for highway driving, while the driver can still use it to communicate instructions to the vehicle according to the current H-mode. Some of the schemes in which a FCSW may be applicable are summarized in the following:

1) **Manual driving:**
   - **Speed adaptive FCSW:** One possibility is a system that smoothly transitions from a steering wheel – at very low speed – to a FCSW for highway driving at higher speeds. Although this has not been tested, the FCSW does not seem *a priori* appropriate for semi-static manoeuvres, such as driving in a parking lot or in a gas station.
2) **Autonomous driving:**
   - **Strategic and maneuvering levels of control:** According to Michon's model, driving is composed of three levels: control, maneuvering and strategic level [42]. The FCSW could be used to control only some of these levels. The driver would communicate to the intelligent system – using the FCSW – the intention of switching lanes (maneuvering level) or exiting a highway to reach a destination (strategic level).
   - **Low probability situation handling with full control:** For autonomous driving, it is conceivable a FCSW instead of a moving wheel. In case of a hazard which the automated system cannot handle (such as occluded lane lines), the human driver could bring forth a swifter regain of control with a FCSW. This driving mode would correspond to level 3 automation according to the SAE $J3016$ automation classification standard.
3) **Shared-control:**

- **Low probability situation handling with shared-control:** Similar to the case above, the driver could use the FCSW to modify or over-ride the AI control manoeuvres or decisions. Input pulses on the FCSW would be superposed to the control response intended by the intelligent tracking system [43]. For instance, if the intelligent system is handling the road curvature but there is an unexpected hazard on the road (such as a large vehicle partially occupying the adjacent lane), the human driver could add a correction to the undergoing control action. This steering pulse would be relative to the steering angle at the wheels applied by the AI, and hence independent of any visual interpretation of the current steering angle.
- **Shared-control through H-mode:** With this scheme, the human driver controls the car at all times, but with the help of the intelligent system. The driver can over-ride the control decisions of the AI according to a preset (or adaptive) H-mode. FCSWs are more analogous to the reins of a horse than a conventional steering wheel, as the position of the FCSW is independent of the yaw rate. Hence transitions in H-mode may be more natural to the driver with a FCSW.
- **Hybrid Mode FCS:** Similarly to the manual mode, the steering system could transition between normal steering wheel and FCS. For example, the system transitions to FCSW when entering an eLane. When the steering system is not locked, this method can be combined with some level of *haptic-guidance* [7].

An additional consideration is the use of brain-computer interfaces [44] to better implement the intent of the human-driver on the vehicle response.

With respect to the configuration of a steering wheel, one obvious advantage of a circular configuration is its shape invariance to changes in steering angle; hence it is uncomplicated to perform suitable steering movements even when $\delta > \frac{\pi}{2}\,\mathrm{rad}$. With a FCSW this is inconsequential, and one can think on the design of new configurations – e.g., the Wrist-Twist Instant Steering system included in some Ford prototypes in the past, or the twin-levers in the recent Honda EV-STER model. In this last example, the driver controls the car with two control sticks – one at each hand. The sticks are coupled to each other, hence the anti-phase filtering properties of the SW are preserved. This system makes use of SBW technology to modify the torque in the sticks to neutralize the perturbations produced by lateral acceleration on the driver.

V. Conclusions

Autonomous driving and shared-control systems are gaining relevance in recent years – partly due to the availability of *steer-by-wire* technology in conventional cars, artificial intelligence developments and an increase in the computational capacity of low-power devices, such as FPGAs. Simultaneously, the evolution of this steering control paradigm opens up new research possibilities towards the design of new steering control devices. In this paper, this subject has been analyzed from the prospect of *force control steering*.

Classical literature, in which force control sticks were tested, reports that in some situations humans perform more efficient control with these devices as compared to conventional control sticks. Herein, these results have been expanded by experiments with human participants, in which they had to control a simulated ground vehicle with a *force control steering wheel*. The results showed that the human-operator adapts promptly to force control and is able to drive a simulated vehicle in a lane keeping laboratory task.

As the transfer functions – acting as transducers between the applied torque by the human and the steering angle at the wheels of the car – are device and task dependent, several mappings were evaluated. It was found that fractional transfer functions are suitable and easy to tune candidates, and that the order of fractional integration is dependant on the speed of the vehicle. It is hypothesized that this may have some relation to the fact that muscular dynamics are well modelled through fractional differential equations; hence a fractional transfer function yields filtering properties similar to those exhibited by the human neuromuscular system.

In this research it was also shown that *force control steering* is particularly efficient for the case in which a driver has to regain control back from an autonomous system in a simulated near collision scenario; the participants were able to avoid an obstacle with larger safety margins and stabilize the vehicle in a shorter time when using the force steering wheel. Although in a real case the driver may not have enough time to react and avoid a collision, the quicker response may be beneficial in realistic situations, such as taking back control when an autonomous vehicle is drifting off the lane – perhaps due to poorly visible road markings, overriding control from an autonomous parking system or when manoeuvring within a gas station.

The generalization of these results from a laboratory task to real-world driving needs further research to assess potential shortcomings, such as vehicle induced hand vibration and lack of interpretability on applied torque when at very slow speeds or semi-static maneuvering. Nevertheless, guidelines towards attainable implementations concerning *force control steering* in highway driving are enclosed in the paper. An example is using the force control device to handle the vehicle only at the maneuvering and strategic levels, while a driver model handles lane keeping at the control level.

As this paper was a first study on *force control steering*, the number of participants was relatively small. An analytical examination discussed designed guidelines – including alternative steering wheel designs such as twin-levers, additional transfer functions (perhaps self-tunable [45]), speed control and a larger sample size – is left for future research.

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